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MNASA As A Test Bed For Carbon Fiber Thermal Barrier Development

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ABSTRACT

A carbon fiber rope thermal barrier is being evaluated as a replacement for the conventional RTV thermal barrier that is currently used to protect o-rings in RSRM nozzle joints. Performance requirements include its ability to cool any incoming, hot propellant gases that fill and pressurize the nozzle joints, filter slag and particulates, and to perform adequately in various joint assembly conditions as well as dynamic flight motion. MNASA motors, with their inherent and unique ability to replicate select RSRM internal environment features, were an integral step in the development path leading to full scale RSRM static test demonstration of the CFR joint concept. These 1/4 scale RSRM motors serve to bridge the gap between the other classes of subscale test motors (extremely small and moderate duration, or small scale and short duration) and the critical asset RSRM static test motors. A series of MNASA tests have been used to demonstrate carbon fiber rope performance and have provided rationale for implementation into a full-scale static motor and flight qualification.

MNASA AS A TEST BED FOR CARBON FIBER THERMAL BARRIER DEVELOPMENT

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INTRODUCTION

MNASA motors, or Modified NASA test motors are used as a final demonstration/evaluation tool to evaluate motor changes prior to full scale RSRM static test implementation. A proposed nozzle change currently being evaluated is the use of woven carbon fiber ropes as RSRM nozzle joint thermal barriers. MNASA testing has been a key leg of this development effort

Currently, all joints in the RSRM nozzle (Figure 1 – joints occur where nozzle sub-assemblies are bolted together) are filled with a two-part RTV that cures in place. Once cured, the backfill material serves as a barrier that isolates the o-ring seal from combustion gasses. The design intent of the RTV filler is to prevent hot gas thermal degradation of o-ring seal capability. Of particular interest is the cowl-to-housing joint, also referred to as joint two. This joint is expected to have the largest dynamic movement and is in a

hot, high-pressure region of the motor. See Figure 2 for a drawing of a fully assembled joint two. Experience has shown that joint dynamics in the motor can be severe enough to fracture the RTV during motor operation. Relatively uniform (around the circumference of the nozzle) fracture of the RTV filler results in a rapid, diffuse joint pressurization event that does not degrade seal function.

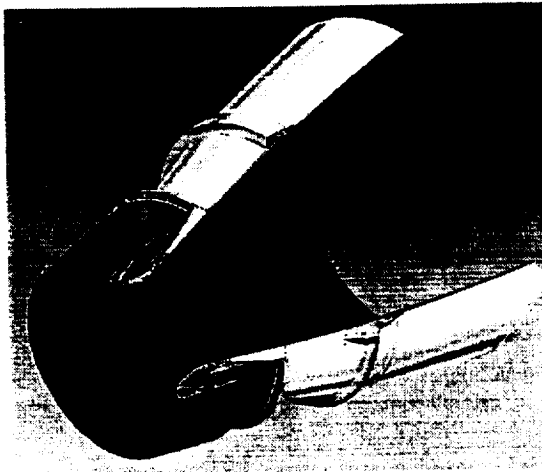


Figure 1. RSRM Nozzle

In addition to a fracture path, there is another, less benign gas path route through the current thermal barrier. During assembly and the RTV backfill process, entrapped air, that is slightly compressed by the influx of RTV filler, can work its way from the interior of the joint and form variable length voids or pockets that are preserved as the RTV cures. During motor operation, as the nozzle liner and RTV ablate and expose the local voids, a gas path, establishing communication between the motor chamber and the joint interior ahead of the o-rings may eventually form. These discrete paths, while rare, can concentrate the flow of hot entrant gas to a particular portion of the joint. In addition to a concentrated hot gas fill jet, joint pressurization in this manner, through a finite number of discrete fill

paths, is substantially prolonged. This hot gas impingement can heat-affect paint or phenolic within the joint. These in-depth joint thermal effects are undesirable. Use of a carbon fiber rope barrier, in place of the RTV, is a very promising means of remedying the undesirable features of the RTV system.

The concept of a carbon fiber rope used as a method of cooling and controlling the flow of gas into the joint was introduced in AIAA 99-2823. It describes testing done to characterize the thermal properties of several carbon rope candidates as well as the rope's applicability to the RSRM nozzle-to-case joint.

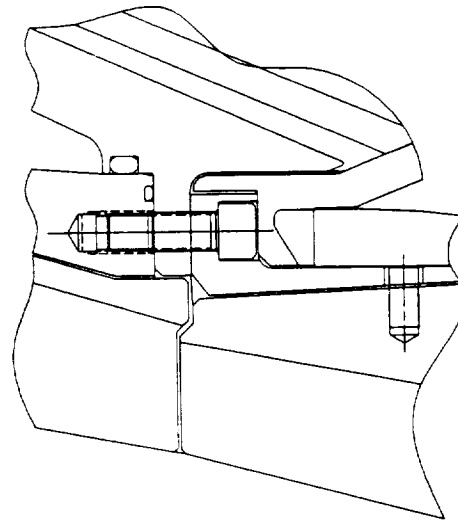


Figure 2. Current Flight Joint 2

The gland design concept was introduced in AIAA 99-2899 in a paper that outlines the thermal performance of CFR (Carbon Fiber Rope) in another joint. The concept involves a method for improving performance during rapid pressurization.

A summary of testing and development for the CFR program was presented in AIAA 00-3566 as an overview of all joint 2 testing to date.

This paper concentrates on MNASA tests and their value as a test bed in the CFR certification program.

MNASA TESTING

MNASA motors are quarter-scale RSRM motors designed to replicate select features of the full-scale RSRM internal environment. These test and evaluation motors are fired on a periodic basis to support development and enhancement without the cost of full-scale motors.

Rope thermal barriers have been in place on four of the last five motors. These tests, unlike supporting, smaller subscale motor tests, have been designed to test the nominally assembled leading thermal barrier candidate in an RSRM configuration and long duration RSRM analog environment.

MNASA-9

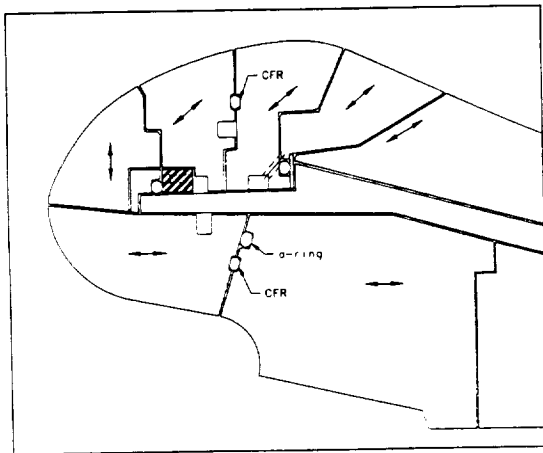


Figure 3. MNASA-9

The first of the quarter-scale motors included as part of this effort, MNASA-9, introduced CFR's as a potential joint thermal barrier concept. The primary objective of this motor test was to test design changes intended to eliminate the formation of RTV voids. Details

regarding RTV void results are beyond the scope of this paper and may be found elsewhere.

Secondary test objectives were to try an alternate thermal barrier material: carbon fiber rope; in two simulated nozzle joints. Two Thermal barrier configurations were tested. One introduced a confined gas path through the RTV to the CFR and tested the CFR's ability to act as a backup to the RTV. The second, a fully vented design (no RTV filler), relied entirely on the CFR to prevent o-ring heat affects. Results were mixed.

The first configuration, with the CFR immediately downstream of the RTV leak path did not defeat the pressurizing gas jet as effectively as was desired. Gas temperatures behind the CFR exceeded o-ring char temperatures. It is important to note that without the CFR, temperatures would have been much higher still.

Interestingly, the fully vented design performed the best of all test sections that actually pressurized the o-rings. Temperatures in the fill volume between the CFR and the o-ring barely exceeded 100°F. The pressure in the 3.85-cubic-inch volume rose to nozzle pressure in about 1.5 seconds.

The results of this add-on "alternative" design sparked a movement to explore design changes to RSRM that would vent joints (i.e. eliminate RTV fill altogether) that have recurring RTV void issues.

With this promising technology demonstrated in MNASA-9, Thiokol initiated a multi-pronged approach to develop viable alternate joint thermal barrier technologies based on CFR. An analytical model effort to develop porous barrier joint filling predictive thermal

models was begun. These models, once developed, would be used to further enhance the design, evaluate CFR for other applications, and support flight production. The second half of the CFR program was to develop a series of small test motors to downselect potential gland designs and rope configurations to combinations that could be adapted to flight. The subscale testing would also generate and measure the validation data required by the predictive models.

Subsequent MNASA motors were used to test baseline designs and validate models and assumptions as the downselection process progressed and as configuration and understanding evolved and matured.

MNASA-11

The objective of the second MNASA motor with carbon fiber rope thermal barrier with a simulated joint 2 was to demonstrate the current (at the time of firing) configuration of the thermal barrier planned for full scale RSRM static test motor FSM-09 (successfully tested May 24 2001). CFR installation and assembly also added to the growing experience base of designing and working with CFR material.

Secondarily, the data collected was to be used to validate the aerothermal models. The models, when complete, will predict gas and wall temperatures behind the thermal barrier during motor operation. While full scale validation and demonstration is required prior to RSRM flight implementation, ultimately, analysis would be used to demonstrate "worst case" acceptable performance of any proposed thermal barrier system.

Third, a highly detailed post-fire inspection would be conducted to identify potential problems in the thermal barrier system, or clues to how it functions. Items requiring test validation included: CFR ability to filter solids; function of the CFR end-to-end splice joint; and any indication of degradation of the rope in concentrated and/or prolonged thermo-chemical exposure.

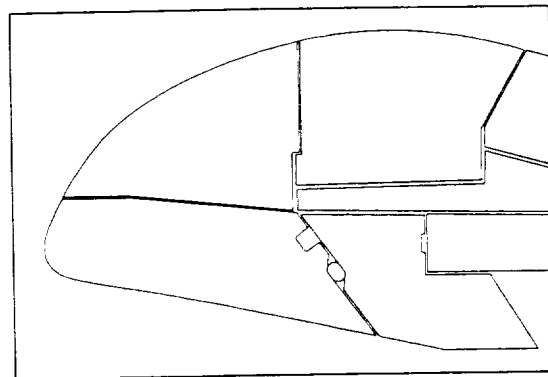


Figure 4. MNASA-11

Actual assembly of the MNASA-11 hardware resulted in a simulated RSRM nozzle joint 2 gap width that was smaller than nominal. This configuration was predicted to yield gas temperatures downstream of the rope that were cooler than those expected with the nominal gap width (more heat transfer wall surface per unit gas influx). Instrumentation consisted of pressure transducers and thermocouples upstream and downstream of the carbon fiber ropes.

Downstream of the ropes, results were qualitatively consistent with the predictions. Temperatures behind the rope were approximately 90°F. This configuration represents the limit of the thermal barrier because similar pressurization tests with cold gasses produced similar temperature rises. Temperature rise behind the barrier during motor ignition matches the drop measured

during pressure tail off. The majority of the heating behind the rope can be attributed to gas compression. Heat from combustion gasses was almost entirely isolated from the region downstream of the CFR thermal barrier.

Results of this test (and others) provoked a change to the way gas temperatures were measured. Conduction and radiation of heat away from the TC bead to the thermal mass of the thermocouple leads, and to the close (cool) wall surfaces in the narrow gaps were considered causes of the unexpectedly low indicated thermocouple temperatures. Estimated gas maximum temperatures downstream were as high as 1130°F. The need for better transient gas temperature measurements in small gaps was recognized and work to improve the gas temperature measurements was initiated.

All gages upstream of the CFR's were lost during nozzle assembly. These data were to have provided insight into the hot side rope boundary conditions.

Since identical objectives for a similar thermal barrier were planned for MNASA-12, it was necessary to ensure that the problems encountered on MNASA-11 were not repeated. Several changes were made to the MNASA-12 instrumentation based on MNASA-11 lessons learned. These, included: increasing the wire diameter, re-routing the wiring, and installing barriers to adhesive squeeze-out.

Post-fire Inspection

The following is a list of the observations made during the disassembly evaluation process:

1) No evidence of sooting was observed past the rope. However, a white residue

was observed just downstream of the rope edge intermittently full-circumference on the aft mating part. None was observed on the nose cap. After the rope was removed from the joint, several areas were also observed in a pattern across the footprint consistent with the fiber braiding pattern of the rope. A sample for chemical analysis was taken. Whitish powder was determined to be ammonium chloride, a propellant combustion by-product.

2) A clear rope "footprint" edge was observed on both mating parts. No evidence of gas jetting around (rather than through) the CFR was observed. The phenolic downstream of the rope was not heat affected.

3) No evidence of gas leakage or jetting was observed at the rope splice joint region. The splice did pull apart at joint separation, each end adhering to the separate joint mating halves.

4) The full upstream face of the CFR was covered in soot and combustion by-products. A clear "footprint" edge was observed on the top and bottom of the rope with no soot extending past this interface.

MNASA-12

Braided Carbon Fiber Rope (CFR, 0.26: Diameter) was installed (two locations) in the MNASA RSRM-12 simulated nozzle joint 2 (Figure 5).

The objective was to evaluate the performance of dual braided CFR thermal barriers in a simulated RSRM nozzle Joint 2 to spread and cool any gas flow into the joint. CFR and nozzle phenolic joint configuration were similar to MNASA-11. The CFR configuration differed from the previous motor in that the CFR glands had evolved to "V" grooves and face mates

and dual (2 CFR's in series) CFR's were used. Additional phenolic material was also removed from the joint downstream of the cold side CFR to simulate the RSRM free volume behind the ropes. This measure was incorporated since analysis had shown that fill volume could have a significant impact on fill time and hence heating of any exposed surfaces.

Post-fire inspection

The dual braided carbon fiber ropes operated as intended. No slag or soot products were observed past the second rope.

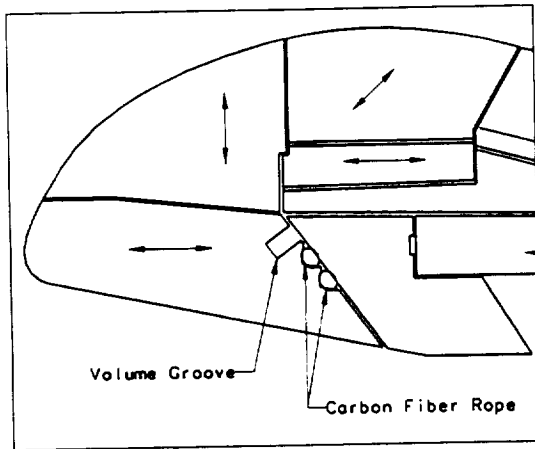


Figure 5. MNASA-12

Instrumentation in the joint included temperatures before, between and aft of the ropes, and pressures before and after the 2 ropes. The two internal temperature gages aft of the carbon fiber ropes had no temperature reaction during the test. The two internal pressures gages aft of the carbon fiber ropes showed no pressure reaction. During the pretest leak check of the pressure transducers, it was discovered that the gages were inoperable. Both pressure gages and the two temperature gages had been covered with excess adhesive, causing a loss of pressure or

temperature readings at these locations. (Show sample results we did get?)

MNASA-13

MNASA-13 again was configured to simulate the nominal RSRM joint 2 configuration with a single (non-redundant), vented CFR thermal barrier and splice. Configuration was a single CFR face gland with nominal geometry. Additional fill volume was added to reflect recent RSRM fill volumes. The splice consisted of butting the cut ends of the CFR together, Teflon taping the butt joint, and potting the hot sides of the splice with RTV DC-732. Figure 6 shows details of the submerged region joint 2 CFR design, instrumentation, and location of the nozzle internal instrumentation joint solder tabs. Pressure and temperature gages were installed upstream (i.e. chamber gas side) and downstream (i.e. control volume side) of the CFR gland. A closed cell polyurethane foam barrier was bonded to the forward end of the nozzle housing to prevent intrusion of the nose inlet-throat inlet ring adhesive into the CFR control volume and adjoining instrumentation, as happened on MNASA-12.

Primary CFR objectives for this firing were to obtain joint response data for model development. (Pressure and temperature measurements) Post-fire inspection data was also collected.

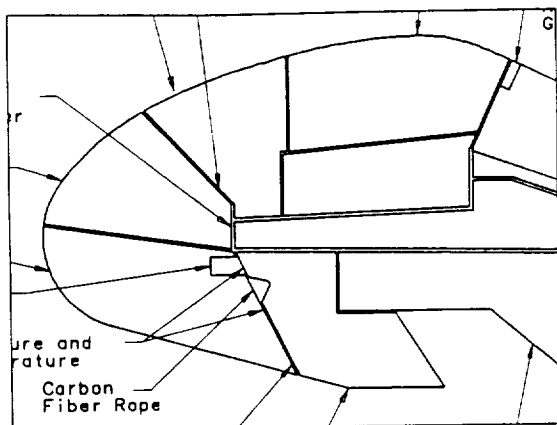


Figure 6. MNASA-13

Analysis Data

Excellent Joint 2 CFR pressure and temperature response were obtained.

The upstream (i.e. chamber pressure side) thermocouples survived most of the motor operation. They were only expected to survive the first second or two. The thermocouples track each other indicating that the temperature fluctuations are real and not artifacts of the thermocouples. The downstream (i.e. backside of the CFR) thermocouples survived full motor burn as expected, and shown on Figure 12.

Both upstream gages performed as expected, and tracked each other within 5 per cent, as shown on Figure 14. One downstream pressure gage was either calibrated incorrectly or malfunctioned, as it appeared to have recorded pressures higher than chamber. Remaining 3 downstream gages performed excellently, and recorded results within 5 per cent of each other.

The data from joint 2 CFR simulation test MNASA-13 was the best yet collected. The high-temperature joint inlet suspended thermocouples, designed to be more representative of gas temperature in the the narrow gap, rapid transients required.

survived over half the motor operating time, and provided the best boundary conditions yet in the vented joint on the chamber side of the CFR barrier. Thermocouples immediately upstream of the CFR survived the entire motor burn time, and demonstrated the thermal protection obtained by placing the CFR barrier deep in the joint. These temperatures were less than 500°F for most of the test. Temperatures downstream of the CFR only reached a peak value of 105°F for a very brief period of time. Pressure rise data was also excellent and for the first time the pressure drop across the full circumferential test article with in-board-directed flow is well known.

Post-fire

Soot and slag deposits were observed along the phenolic surfaces leading up to the CFR full-circumference. Alumina spheres (slag droplets/balls) and black sooting were observed.

The CFR was intact full-circumference with a slag/soot deposits along the outboard (hot side) face. This was typical of other hot fire CFR tests (MNASA-11, 12, etc.). No gas paths were observed across the CFR footprints either within the CFR gland (aft part) or across the top side (between CFR and forward nose cap) of the CFR. No concentrated fiber frayed locations were observed on the CFR although typical loose fibers were observed intermittently.

The RTV at the splice was not correctly applied. RTV extended along the CFR beneath the CFR as well as past the CFR. Also, the RTV did not extend past the ends of the Teflon tape as required in full-scale assemblies. The Teflon tape that was exposed to upstream gas temperatures

does not appear heat-affected. Besides the front/hot side edge of the RTV, the RTV appeared unaffected by heat. No leakage or gas flow was observed through or by the splice location.

The pressure transducer caps were observed to be unplugged. The thermocouples upstream of the CFR were encrusted with soot/slag products but appeared to be intact once the combustion products were removed to inspect the wires. The thermocouples downstream or past the CFR were intact and were not contacting the phenolic surface (clear shadows could be seen under lighting as well as directly underneath each thermocouple). This observation indicates that the TC readings are more representative of gas temperature (desired) than they are of wall temperature.

The foam adhesive barrier prevented nozzle adhesive from intruding into the simulated volume groove. The foam was damaged due to the nose cap machining process but functioned full-circumference. The simulated volume groove was free of nozzle adhesive. The surrounding phenolic surfaces appeared pristine and non-heat affected.

Several small balls of what at first appeared to be slag were found downstream of the CFR, but were later identified as melted nylon threads from the CCP slit tape. Samples collected will be analyzed. No gas intrusion indications across the CFR footprint were observed in the corresponding locations.

SUMMARY

Carbon fiber rope has proven to be highly effective in removing heat from propellant gases as they fill heat-sensitive volumes. Testing has identified the preferred gland

configuration for joint two and MNASA motors confirmed the performance in a larger-scale motor. All test data and analysis support demonstration of a CFR face gland configuration in a full-scale static test motor.

Small, subscale motors were useful in defining and screening CFR configurations and in developing advanced model validation instrumentation techniques. The MNASA motors served as an integral development step in preparing CFR joint configuration, processing, and analysis for full-scale static test implementation. In this role, the MNASA motors provided an excellent tool to demonstrate two things: First, CFR performance in RSRM environment analog joints in a variety of configurations, and second, the long duration CFR/joint exposure.

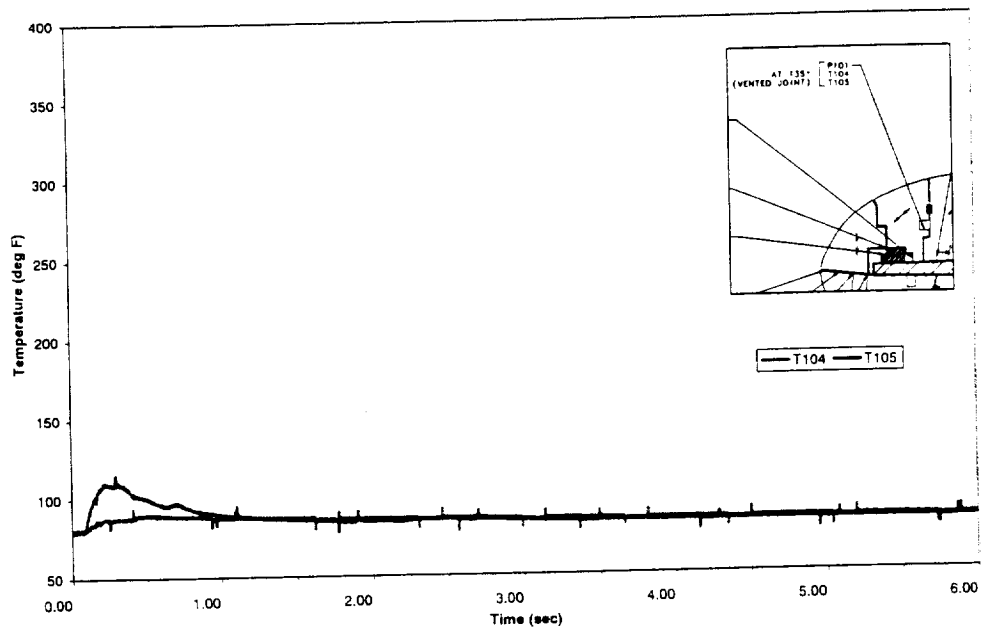


Figure 7. MNASA-9 downstream temperature data

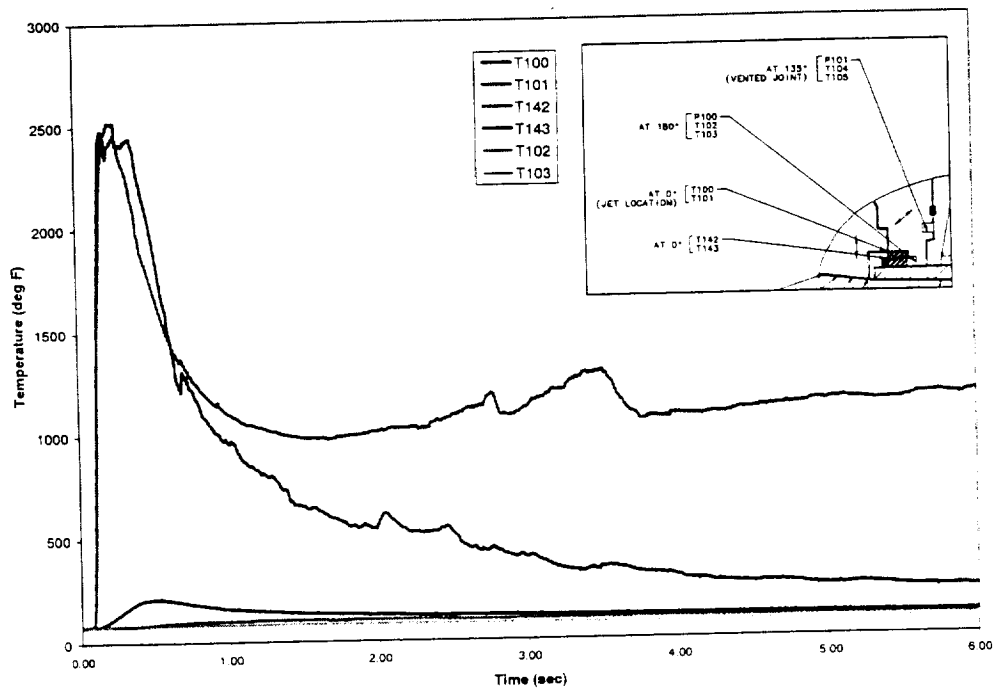


Figure 8. MNASA-9 data

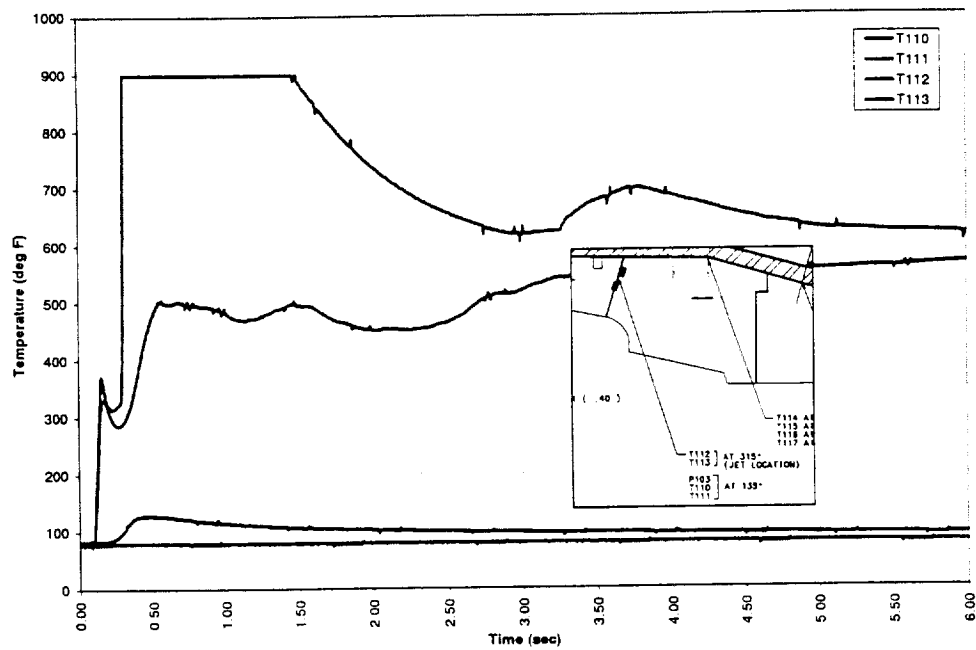


Figure 9. MNASA-9 data

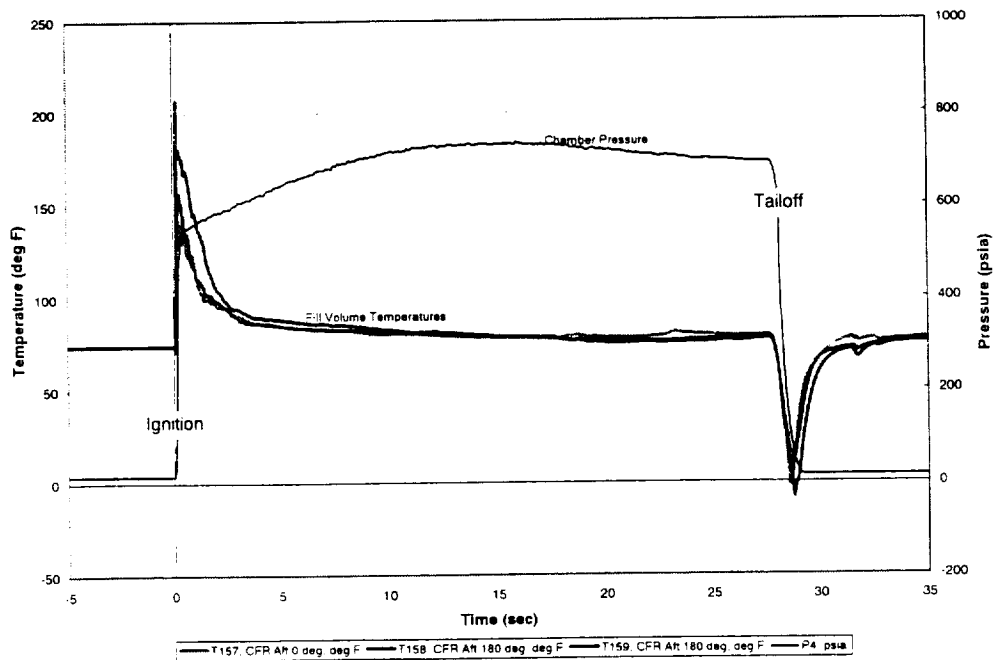


Figure 10. MNASA-11 case pressure and downstream data

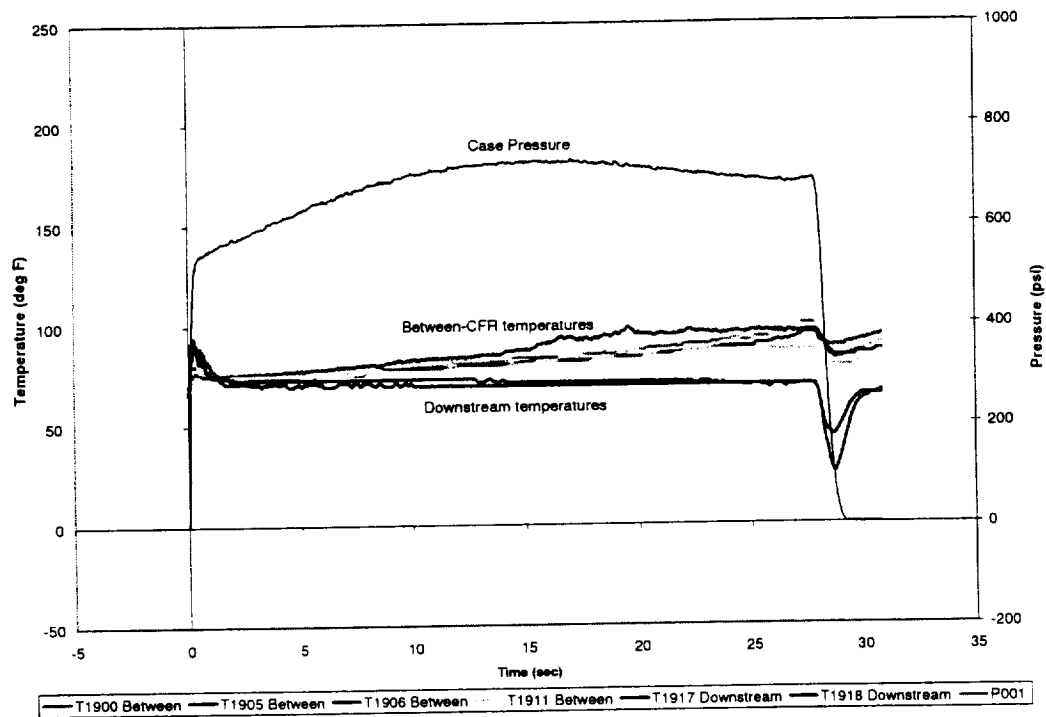


Figure 11. MNASA-12 case pressure and downstream data

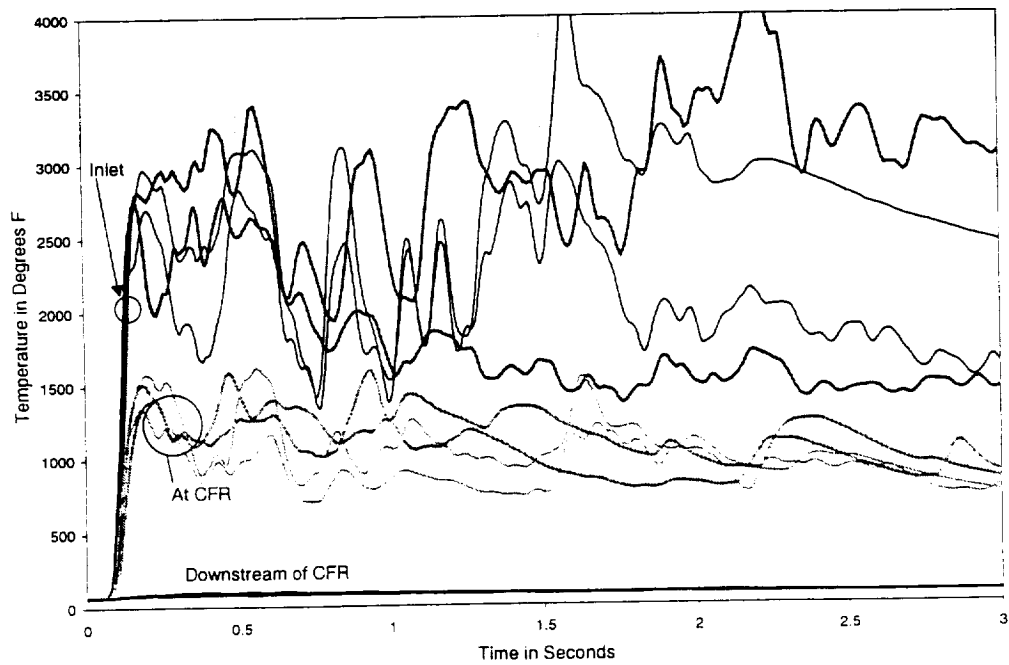


Figure 12. MNASA-13 temperature data

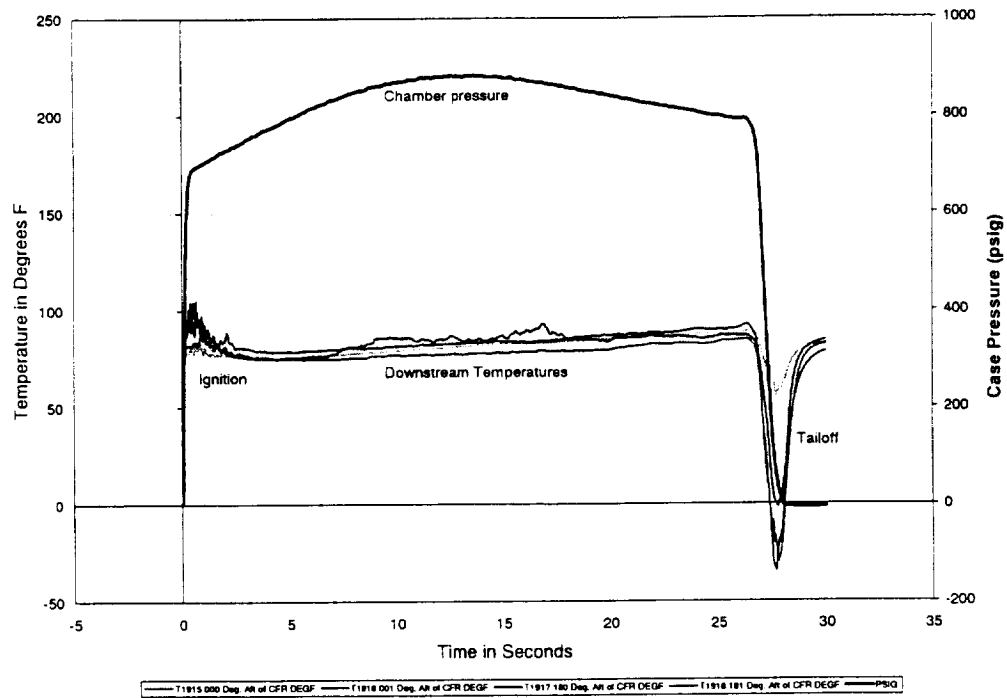


Figure 13. MNASA-13 downstream temperature and pressure data

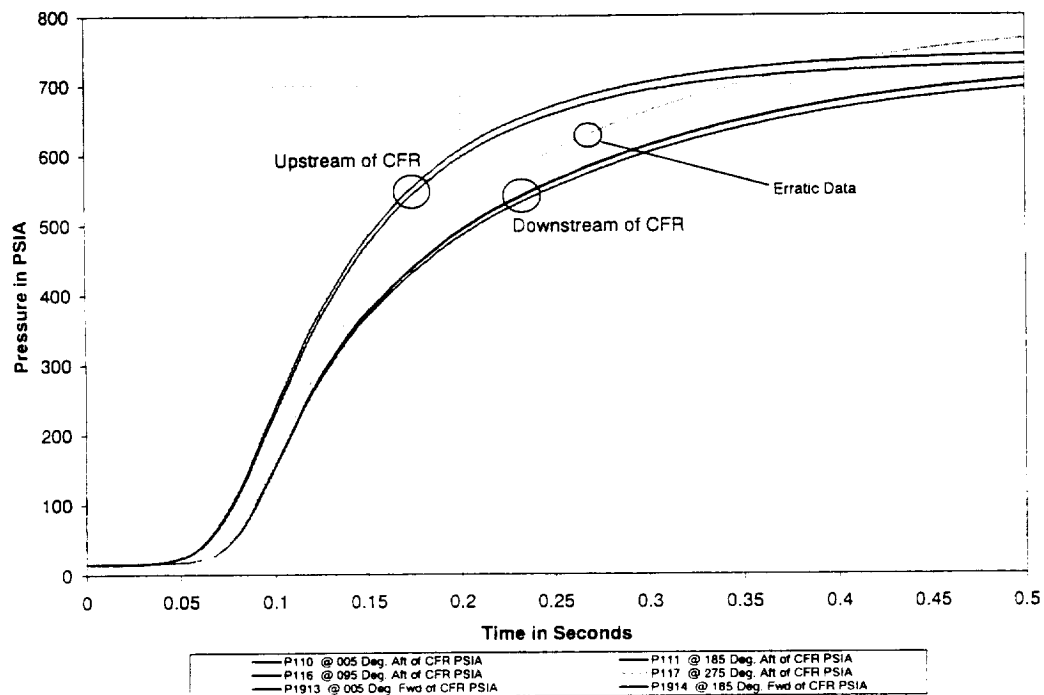


Figure 14. MNASA-13 fill transient pressure data